CONTRIBUTIONS TO THE MINERALOGY

OF THE

NEWARK GROUP IN PENNSYLVANIA

THESIS

PRESENTED TO THE FACULTY OF THE GRADUATE SCHOOL OF
THE UNIVERSITY OF PENNSYLVANIA
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE
DEGREE OF PH.D.

BY

EDGAR THEODORE WHERRY, B.S.
PHILADELPHIA.

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INTRODUCTION

WHILE the Newark Group of the Eastern United States has attracted considerable attention from geologists during the past few years, there is still a lack of knowledge concerning certain of its features. In 1907, while engaged in a study of the copper deposits of this terrane, the writer had occasion to inquire into the nature of the change from a red to a gray color so frequently observed in the sediments where affected by igneous rocks, and into the origin of the secondary minerals occurring in the cavities in the latter. Search through the literature failing to reveal any satisfactory data upon these points, a paper on the copper ores was prepared and published without including reference to them,[1] but later, when opportunity presented itself, a study of them was undertaken, and its results are recorded in this paper.

In the course of the work on the copper deposits it had appeared desirable to examine as many of the Newark traps as possible, and in the vicinity of the town of Jacksonwald, Berks County, four miles southeast of Reading, the rocks were found to present an unusually favorable opportunity for study. Here was discovered the only occurrence of extrusive basalt as yet observed within the boundaries of the State; and here an intrusive mass was found to be so closely associated with this extrusive one that a direct comparison of their structural features and their metamorphic effects upon the surrounding sedimentaries could be made; while the relations of the secondary minerals developed in the extrusive rock seemed capable of throwing some light on their origin.

To Professor Amos P. Brown, under whose direction this study has been carried out, the most cordial thanks of the writer are hereby extended, in appreciation of his ever-ready advice, encouragement, and assistance, without which this paper would never have been prepared.

Grateful acknowledgment is also made to the Corporation of the University of Pennsylvania for award of a Harrison Fellowship in Mineralogy in 1907–08, and a University Fellowship in Mineralogy in 1908–09; and to the Trustees of the Wagner Free Institute of Science of Philadelphia for award of a Fellowship in Chemistry.

GEOLOGY OF THE DISTRICT

THE First Geological Survey of the State of Pennsylvania overlooked the presence of igneous rocks in the Newark to the southeast of Reading. In the course of the far more detailed work carried on by the Second Survey, however, the occurrence of such rocks was soon observed, and in the report on the Geology of the South Mountain Belt of Berks County,[2] they were described by Mr. E. V. D'Invilliers in the following words:

"The two concentric trap dykes here met with in Exeter Township form a prominent landmark in the topography of the country, rising from the west, where their summits are about 400 feet above ocean level, to the east, where they reach above 500 feet.

"The level of the red shale country surrounding them and contained between their walls is about 300 feet, which unlike the Boyertown deposit, has not been changed in the least either in the position or character of its beds from the usual succession of shale and sandstone so familiar in the general formation."

The northern "dyke" is further described as "dark, fine-grained trap, containing a good deal of augite"; the southern one is said to be lighter in color, and the occurrence of a "variegated red shale and sandstone" at its lower boundary is mentioned, although elsewhere it is stated that the "sandrocks south of Jacksonwald have scarcely been changed by the two trap dykes there."

This district received no further attention until 1908, when two brief notes upon it were published simultaneously. Dr. A. C. Spencer, in describing the occurrence of iron ores on the Esterly farm, states:[3] "The diabase [associated with the ore] is the outer of two concentric curving sills which follow the bedding of the Mesozoic shales and sandstones, here thrown into a rather sharp synclinal fold."

In the paper on the Newark copper deposits, mentioned in the introduction, the present writer announced that the inner of these two trap masses is not a sill, but an overflow-sheet, presenting as evidence the vesicular character of the rock, and the complete absence of alteration in the enclosing shales. Further proof of the correctness of this interpretation is given herewith.

The accompanying geological map, Plate 1, shows the areal distribution of the rocks. The Newark is considered to be faulted against the Cam-

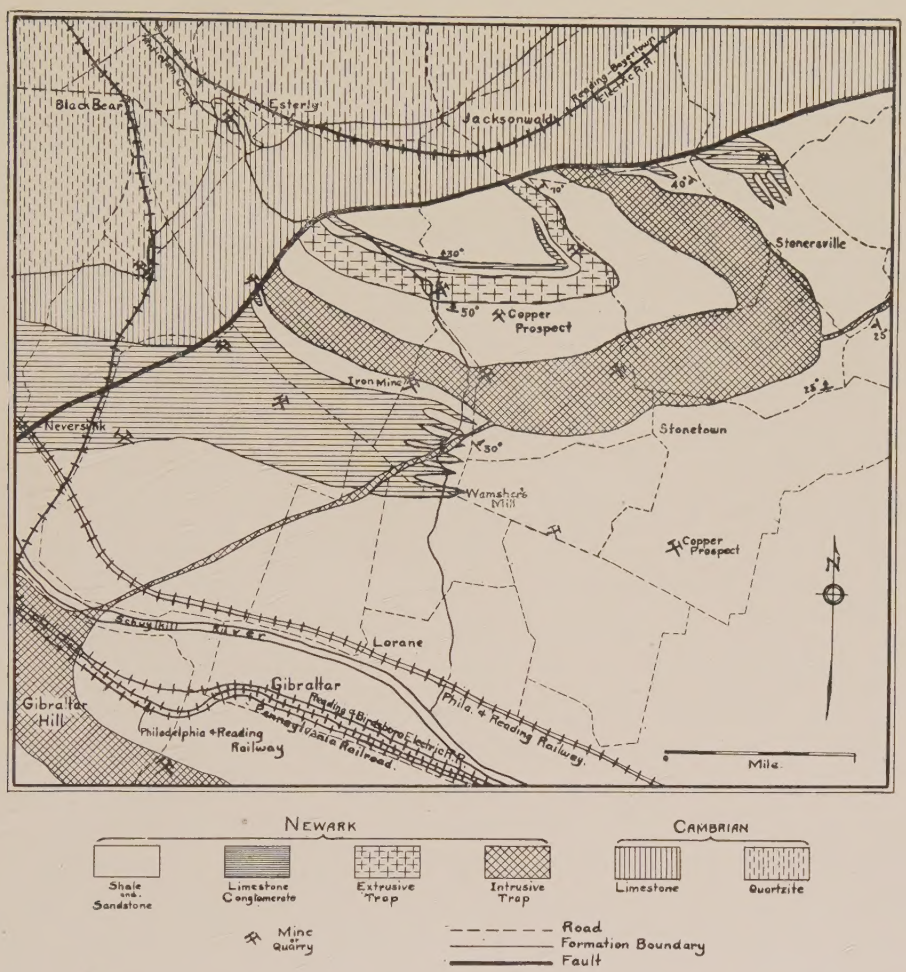
brian limestone, which lies conformably upon the quartzite of the same age forming the hills to the north, because of the abrupt disappearance of the trap masses at the boundary, and the fact that the close synclinal to which the trap hills owe their shape also ceases there, the structure of the Cambrian rocks being quite different. Like many of the faults limiting the Newark belt, however, it does not continue to determine the boundary for any great distance, but turns on the southwest into the Newark, soon becoming obscured, and to the northeast into the Paleozoics, so that from a point north of Stonersville eastward the boundary is a true overlap, up to the next fault below Boyertown.

The trap masses are, as already mentioned, indicated by prominent elevations, although they can not be accurately mapped on this basis, for in places the sedimentary rocks are exposed far up the flanks of the hills, and again the trap descends to the level of the streams. The exact boundaries between the trap and shale can, however, be determined by the character of the soil, especially in the case of the northern mass, where the change from red-brown shale soil to the yellow of that derived from the trap is particularly marked. The present map, representing the results of some two weeks of field work, has been prepared as carefully as possible with this point in view.

The section through these hills cut by Antietam Creek affords the best view of their character and structural relations, and may therefore be described in detail. Starting from Wamsher's Mill, on the east side of the creek, one mile north of Lorane Station, on the Philadelphia and Reading Railway (called Exeter on the older maps), and proceeding northwards along the mill-race, the first rock encountered is a bright red sandy shale, dipping 30° north 30° east. With this there are interbedded several layers of limestone-pebble-conglomerate, showing that the large area of this rock to the west does not end in a rounded point, as indicated on the previous maps, but thins out gradually and is replaced eastward by the shale. A lens of yellow sandstone is also exposed here, containing an abundance of plant remains, apparently pieces of leaves and stems, but in too fragmentary condition for determination.

Three-eighths of a mile above the mill the first trap appears, in the form of a dike of rather fine grained diabase about 50 feet wide; this can be traced southwestward for some three miles, to connection with the large body of igneous rock forming Gibraltar Hill, as will be described below. It appears to stand practically vertical, and has altered the shale to a distance of 15 feet,

PLATE I



GEOLOGICAL MAP OF THE JACKSONWALD DISTRICT.

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changing its color from red to gray. The presence of other dikes nearby is suggested by the fragments in the fields, but they are not exposed in place.

For some 700 feet further north the sediments are of the normal red sandy shale character, but the dip gradually increases to 50°. Then evidence of alteration begins to appear; the shale is first, to a distance of 125 feet, strongly indurated, without change in color. The succeeding zone of "variegated red shale and sandstone," about ten feet wide, is evidently the result of the same degree of metamorphism affecting layers of different composition. For 50 feet further the shale is light gray and very hard, a sort of hornfels, and then comes the solid trap. The actual contact is somewhat obscured by weathering, but the base of the trap is quite conformable with the bedding of the shale. In the immediate vicinity of the contact the trap is rather fine grained, but gradually increases in coarseness upwards, the maximum of 1 inch crystals of feldspar and pyroxene being reached about 50 feet below the upper surface. The exposure is 900 feet in width, corresponding to a thickness of 800 feet; and on the east side of the creek it ceases abruptly at a small transverse stream, north of which gray altered shale fragments are abundantly present in the soil. The west bank of the creek is here quite steep, however, and exposures of trap continue over 100 feet beyond the first sign of shale on the east side. A few boulders of finer grained material appear at the immediate contact, within five feet of greatly indurated gray shale dipping about 60° north 40° east. The gray color persists to a thickness of over 20 feet, but the exposures are not sufficient to permit of following the changes closely, as could be done below the sheet. The normal red color is, however, soon resumed, and continues for half a mile northwards along the creek.

Just below the dam of Althouse's mill-pond igneous rock again appears, but this time without warning, the soil up to the solid trap exposure remaining bright red, and, on the west bank, above the gate to the race, fresh sandy red shale outcropping on the hillside within two feet of the trap. The boundary between the igneous and sedimentary rocks is here a beautifully sharp one, an abrupt change from red soil derived from the shale to the yellow soil produced by the weathering of the iron-bearing silicates in the trap being traceable across the fields for a considerable distance.

On the east side of the creek the hill rises suddenly from the meadow below and the contact is obscured by boulders; but about 200 feet back along the base of the hill a rather peculiar relation appears. A small quarry has been

opened here, exposing the underlying shale, dipping 50° north 20° east. Westward this extends below the surface of the ground, the trap overlying it in a perfectly conformable manner, but on the east the trap breaks across the beds of the shale, and is exposed to a distance of five feet, apparently as a sort of dike. The soil of the meadow effectually conceals the further extension of this dike, so that it can not be definitely proved that it connects with the intrusive sheet below, although it is quite possible that such is the case.

This shale is slightly metamorphosed, its normal red color being changed to dull brown, but the intense alteration, such as is exhibited below the southern sheet, is entirely lacking. The trap is welded to the shale, and although weathering has caused considerable disintegration, specimens can be secured showing this contact. The trap is extremely compact, dense, and fine grained throughout the greater part of this exposure, but about two feet above the contact on the shale it contains occasional amygdules filled with quartz, cylindrical in outline, and averaging one-half inch in diameter by three inches long. These are no doubt to be interpreted as gas or steam cavities lengthened by the flow of the viscous lava; the direction of lengthening is north 25° west.

A series of trial excavations for road metal has been made along the road north of this point, so that the trap is well exposed throughout its entire thickness of 500 feet. The fine grained character shown at the lower contact persists upwards for over a hundred feet, with occasional slightly porphyritic areas. Then minute cavities begin to appear, and these increase in number gradually, until at the top the rock is highly vesicular. The cavities are in part filled with various secondary minerals, chiefly calcite, prehnite and datolite, the last being confined to a narrow layer about 350 feet below the top; to these attention will be further directed below.

The extremely porous character of the upper part of the trap mass having rendered it particularly susceptible to weathering, the contact with the overlying shale is nowhere exposed. In the road bank, however, there occurs a broken-up, scoriaceous material, impregnated with calcareous red mud, along with fragments of red shale which do not show the slightest sign of metamorphism. And red shales, with occasional beds of conglomerate and sandstone, continue to be exposed along the creek to the boundary of the Newark half a mile to the north.

There are two possible ways in which sheets of igneous rock interstratified with sedimentary rocks may be produced. In one type, known as extrusive, the molten lava has been poured out over the surface of the depositing sediments,

and has then been buried beneath further accumulations of the same material. In the other, the intrusive type, the magma has never reached the surface, but has lifted the layers of sediment previously formed and flowed out between them, by virtue of the buoyant force due to its greater specific gravity. The criteria for distinguishing these two modes of origin are numerous, and although the presence of one or two of them might not be sufficient to decide a doubtful case, when several occur in conjunction, there can be little question as to the correctness of the origin indicated.

These criteria, first worked out in detail by Prof. W. M. Davis,[4] may be grouped in the order of their relative weight as follows:

Type of Phenomena.	Extrusive Sheets.	Intrusive Sheets.
Chemical.	Slight alteration of underlying, and no alteration of overlying sediments.	Intense metamorphism of underlying, and especially of overlying sediments.
Lithological.	Fine grained, with vesicular texture prominent, at least near the top, and usually throughout the mass.	Coarse-grained, except at contacts, rarely showing trace of vesicular texture, and then only locally.
Structural.	Must be strictly conformable with the enclosing sediments. May be overlain by trap conglomerate, or by tuff beds. May contain xenoliths near base only.	May break across the beds of the enclosing sedimentaries and send offshoots into the overlying ones. May be bounded by friction breccias. May contain xenoliths both at base and top as well.

From the descriptions of the two sheets in the present area given above it appears that they are of different origin, but in view of the divergence of published views on the origin of the trap sheets of Pennsylvania in general, it seems desirable to discuss the evidence still further. Taking up first the southern sheet, this shows more intense metamorphism of the underlying sediments than has ever been observed in connection with any known extrusive sheet. This, however, would not be sufficient to decide the question, were other evidence not available. It was shown above that the overlying shale is also intensely metamorphosed. There can not be the slightest doubt of the correctness of this observation, for chemical and petrographical examination shows this shale to be changed from the normal types of Newark sediments in exactly the same way as the shales underlying the sheet. It might be suggested that another hidden bed of trap exists at a horizon just above this altered shale,

and has produced the observed alteration at its lower contact. This is, however, not possible because (*a*) the exposures above the trap sheet show unaltered shale overlying the altered phase directly, without room for a trap sheet of more than a few inches thick; and (*b*) the alteration decreases upwards, as the main trap sheet is receded from, instead of downwards, as would be the case if produced by a second, overlying sheet.

This sheet is further holo-crystalline throughout, and most coarsely grained near the top, indicating the slowest cooling there, precisely the reverse of what would occur in an extrusive flow. At the immediate contacts it is fine, and shows by its texture that it has been rapidly chilled, as is to be expected when molten trap flows against cold rock surfaces. The phenomena are alike at both upper and lower contacts, whereas if the sheet had been extrusive, and cooled with its upper surface exposed to air or water, and the lower against rock, very different textures must have been produced. There is not the slightest trace of vesicular texture at any place throughout the whole exposure of this sheet, yet present day lavas are usually prominently vesicular, owing to the escape of steam during solidification.

Finally, the structure of the southern sheet indicates its intrusive character, in that it appears both to be unconformable with the sedimentaries, and to vary in thickness, the effect upon the outcrop being well shown in the geological map. Such unconformity would, of course, be impossible in an extrusive sheet; so its intrusive character would seem to be proved, in so far as it is possible to prove any geological theory.

The evidence in the case of the northern sheet points with equal force to the other mode of origin. The underlying sediments are practically unmetamorphosed, the greatest effect observed being a slight darkening of the color to a distance of three feet from the contact, and no change at all being detectable in many places. But here again the conclusion drawn from the lower contact phenomena is of far less weight than that derived from the effects exhibited above the sheet. The uppermost portion of the sheet presents, as mentioned above, a trap breccia, cemented together with soft calcareous red mud, overlain by shales composed of the same material, failing to show at any point the slightest trace of metamorphism. The whole suggests very clearly an advance of water over the cold, solidified trap, the currents at first breaking up to a slight extent the surface of the latter and then depositing over it the red mud characteristic of Newark sedimentation.

The texture of this sheet also furnishes a similar inference as to its origin. While compact and fine grained below, it gradually becomes vesicular upwards, being toward the top crowded with cavities of all sizes, up to an inch in diameter. From observations made on modern lavas it is known that such cavities are produced by the escape of steam during the solidification of the molten material, and that they only form at or near the surface exposed to the air, where the cooling is rapid but at the same time the pressure upon it is low. In those portions of the sheets which cool slowly at some depth, so that a greater pressure is exerted, steam bubbles are of comparatively rare occurrence. The glassy character of the present rock, described fully below, is also in agreement with the assumption of rapid cooling at the surface. It stands in strong contrast to the rock of the southern sheet, which, throughout its whole extent, does not show the slightest trace of glassy material, but is everywhere completely crystallized.

This northern sheet is also strictly conformable with the sediments surrounding it. The outcrop of its northeastern arm is shown on the map to be rather narrower than that of the western one, but this does not indicate a variation in thickness, for the dip of the beds as a whole is greater in the latter place, the thickness being actually constant at 500 feet, throughout the length of the exposure. This corresponds to what would be expected in the case of molten material flowing out over a perfectly level surface, whereas it would be quite exceptional in the case of an intrusion. The evidence for the extrusive origin of this sheet may thus also be regarded as complete.

Recognizing the divergence in origin of these two closely associated sheets, the question now arises, Do they both belong to the same period of igneous activity, or are they of different ages, as has been established in the case of the intrusive and extrusive sheets in New Jersey? While no direct evidence bearing on this point can be obtained at the present locality, it would seem quite probable that the two sheets were produced by the same eruption. As shown on the map, a dike starts out from the upper side of the great mass of intrusive diabase forming Gibraltar Hill and those adjoining it, and can be traced continuously to the base of the intrusive sheet below Jacksonwald. The inference seems justified that the latter represents a small portion of the same magma which has found its way upwards. But it is hardly likely that it would stop a few hundred feet below the surface, for cracks or fissures through which further ascension could take place would be expected to become more abundant as the

surface is approached. And since a dike or dikes connecting the intrusive with the extrusive sheet may well have been removed by erosion or remain hidden in the low ground between the hills, this is regarded as the most reasonable interpretation of the relations in the Jacksonwald area.

Before leaving the discussion of the geological relations of the trap sheets, a word should be said concerning the character of the surface at the time of the eruption of the extrusive mass. In Massachusetts and Connecticut there is good evidence that the Triassic lavas flowed into deep bodies of water. In the case of the First Watchung Mountain in Northern New Jersey it has recently been shown that while it flowed over dry land for the greater part of its course, there was also a shallow lake, in the vicinity of the city of Paterson, whose waters, converted into steam by the intense heat of the molten material, caused a sudden cooling and shattering of the latter. Although the extent of the sheets here considered is very small compared to some of those in the other places, the features shown are none the less interesting. There is not the slightest sign of contact of the trap with a body of water, the base being solid and compact at every exposure. Moreover, the sediment could not have been in the condition of soft mud, as may be seen to be the case below the First Watchung sheet at Upper Montclair, New Jersey. There the base of the trap is very irregular in outline, while here it is comparatively even and straight, showing that the material must have been rather dry and solid at the time of the eruption. That the Newark sediments were frequently exposed to the atmosphere is generally recognized from the abundance of sun-cracks, but we have here evidence that they also became hard and firm at the surface, without requiring to be deeply buried beneath subsequent deposits.

A note should also be added concerning the relations exhibited by the other trap masses in the Newark Group in Pennsylvania, for, as appears from the conflicting statements concerning them in the literature and from the extremely inaccurate manner in which they were mapped by the Second Geological Survey of the State, they have received but little attention in the past. In the course of the present study practically all of these traps east of the Susquehanna River have been examined; they have been found in every case to present relations similar to those of the southern sheet in the Jacksonwald area, the most striking as well as the most conclusive feature being the metamorphism exhibited by the overlying sediments, and are unquestionably to be considered as intrusive in origin. The upper sheet at Jacksonwald is apparently the only one in which there is the slightest indication of solidification at the surface of the earth.

PLATE II

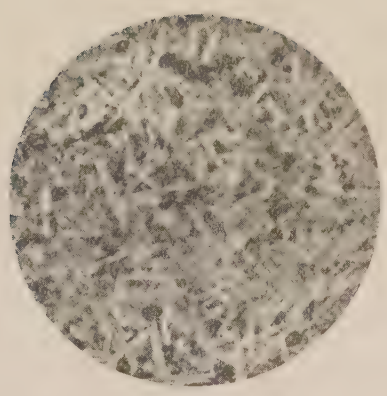

Figure 1.—Diabase, upper surface of intrusive sheet, x 15. Crossed nicols.

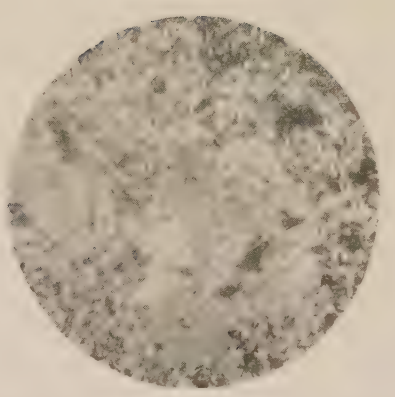

Figure 2.—Basalt; porphyritic phase near base of extrusive sheet, x 10. Crossed nicols.

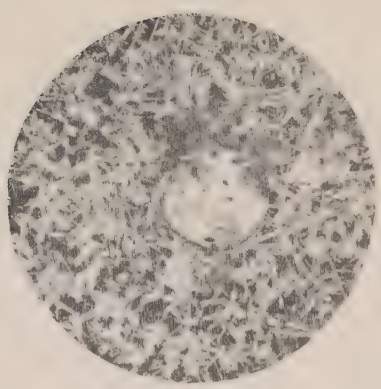

Figure 3.—Basalt, with calcite-chlorite amygdule, from "datolite zone," x 10. Ordinary light.

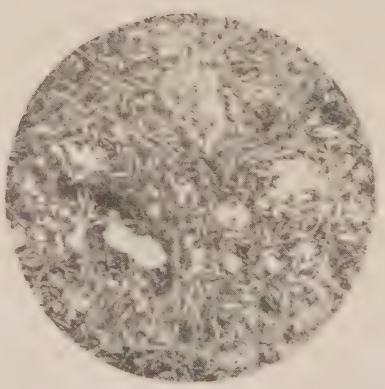

Figure 4.—Basalt glass, with steam-bubble cavities; upper surface of extrusive sheet, x 10. Ordinary light.

PETROGRAPHY OF THE IGNEOUS ROCKS

MICROSCOPIC examination of thin sections of the southern mass, which, as shown above, is to be regarded as intrusive, shows it to be a typical diabase, quite similar in character to the many other occurrences in the Newark of Pennsylvania, and to the Palisade-Rocky Hill sheet extending across New Jersey. The minerals present are plagioclase feldspar and augite, with occasional grains of olivine and of magnetite. The plagioclase is in long slender blades, twinned according to the albite law, so that in polarized light they show dark and light bands running lengthwise. The maximum angle of extinction observed on crystals cut perpendicular to this twinning plane, when the parts become dark at equal distances from the plane, is about 40°, so that the feldspar represents a basic labradorite. These feldspars interlace to form a close network, the other minerals filling up the interspaces, presenting the characteristic diabase texture. The principal mineral in this position is augite, greenish gray irregular grains, often showing slight alteration to chlorite. The olivine and magnetite are usually in smaller grains, more or less surrounded or enclosed by the other minerals.

At both the upper and lower contacts the character of the rock changes slightly, becoming much finer grained, and in the sections an increase in the amount of olivine is noticeable, the grains of this mineral becoming as large as the augites. Even at the very contact, however, there is no appearance of glass, and in this the greatest contrast with the northern sheet is found. (See Figure 1.) The sediments at the contact show dull brownish yellow epidote taking the place of the red mud of the unaltered shales, and occasional minute dots of magnetite.

The most striking feature of the sections of the northern trap sheet is the presence of considerable amounts of nearly black glass, in which the other minerals, feldspar, augite, olivine and magnetite are embedded. The feldspars are similar in shape to those of the other rock, but have slightly less extinction angles, usually about 30°, indicating their greater acidity. The augite and olivine are in small grains, sometimes showing crystal outline, and occasionally enclosing groups of magnetite crystals. Examination of the glass under high power shows that its dark color is due in part to its containing abundant magnetite, and it is also full of feldspar, either in minute needles or in spherulites.

The trap near the base of the sheet is distinctly porphyritic, and its sections show large equidimensional feldspar crystals embedded in the groundmass containing the usual blades of the same mineral. (See Figure 2.) Two stages of crystallization are thus represented, the large crystals having perhaps been formed before the extrusion of the magma. A section of a specimen from a height of 100 feet shows no trace of this porphyritic texture, but in it the cavities begin to appear, most of them being approximately circular in outline, and filled with calcite, occasionally enclosing flakes and concentric groupings of a chloritic mineral, showing a strong pleiochroism from dark bluish green to pale yellow. (Figure 3.)

As noted in the description of the geology of the region, the top of the sheet has been so deeply weathered that there are no good exposures, but the fragments mingled with those of the overlying shale consist of a highly vesicular slag-like material. A thin section made of this showed it to consist chiefly of dark gray glass, containing feldspar in decidedly smaller amount than the lower portions of the sheet, and quite free from olivine and augite. (See Figure 4.) This no doubt represents the surface of the flow, and it is very similar to material found in corresponding positions in the Watchung Mountains in New Jersey. Sections were also made of the shale immediately below this extrusive sheet, and they showed but little difference from the ordinary unaltered sediment, with the exception of the presence of considerable crystalline calcite. There is certainly no development of secondary minerals, such as observed in the rocks underlying the southern sheet.

The results of this microscopic examination are thus in complete agreement with those of the structural studies of the trap sheets, and add a finishing touch to the proof of their difference in origin.

METAMORPHISM OF THE SEDIMENTARIES

ONE of the principal objects of the present study was, as mentioned in the introduction, the determination of the character of the change in color so frequently observed in the metamorphosed sediments of the Newark Group. That the bright red color which constitutes such a striking and characteristic feature of these rocks is produced by a small percentage of ferric oxid is generally recognized. But no attempt appears to have been made to decide whether the gray color developed in the altered rocks is due to the removal of this iron, to its reduction to a lower state of oxidation, or to its entering into new minerals without change of state.

It seemed first desirable to ascertain the composition of the unaltered shale, and for this purpose a sample was obtained from the exposure on the hillside west of Antietam Creek, two feet below the base of the extrusive sheet. Standard methods of analysis were employed, chiefly those of Dr. Hillebrand's papers;[6] the ferrous iron was determined by the Pratt method, as modified by Mr. R. B. Gage,[7] and the water by loss on ignition, with correction for the carbon dioxid, obtained directly. In order to gain some idea as to the character of the minerals present, the sample was first boiled with 20% hydrochloric acid, and the solution and residue analyzed separately. The following results were obtained:

	Soluble in HCl.	Insoluble in HCl.	Totals.
SiO_2	0.56	75.62	76.18
Al_2O_3	0.48	5.68	6.16
Fe_2O_3	3.72	0.92	4.64
FeO	1.10	....	1.10
CaO	4.72	trace	4.72
MgO	trace	none	trace
CO_2	4.40	....	4.40
H_2O, 110°	....	....	0.54
H_2O, ign.	....	....	2.10
			99.84

From these data the mineralogical composition of the rock was readily calculated. The silica is evidently present in two forms, as free quartz and in combination with alumina as kaolinite, a small amount of this latter mineral having dissolved in the acid, although most of it is insoluble. The ferric oxid appears to be all in the form of hematite, the insoluble portion representing particles enclosed in the cracks in the sand grains. The ferrous oxid was

found to be soluble in dilute sulfuric acid, when boiled in a current of carbon dioxid, and has therefore been calculated as siderite, although the significance of the presence of this mineral is not clear. The water given off below 110° has not been used in the calculations, as it probably represents what is mechanically held in the fine powder; the amount found above this temperature agrees almost exactly with the theoretical percentage present in the kaolinite calculated from the alumina. The percentage of these minerals obtained is as follows:

Quartz, SiO_2	69.38
Kaolinite, $H_4Al_2Si_2O_9$	15.69
Hematite, Fe_2O_3	4.67
Siderite, $FeCO_3$	1.78
Calcite, $CaCO_3$	8.48
	100.00

The mottled red and gray phase of shale occurring some sixty feet below the base of the intrusive sheet appeared to be well adapted to determine the nature of the alteration produced by the heated waters given off during the solidification of the trap. A specimen three inches long was obtained, bright red at one end and pale gray at the other, and samples from the extremities were analyzed in the same manner as the unaltered shale described above. The red portion contained:

	Soluble in HCl.	Insoluble in HCl.	Totals.
SiO_2	0.33	77.37	77.70
Al_2O_3	4.09	5.63	9.72
Fe_2O_3	3.94	2.41	6.35
FeO	....	0.69	0.69
CaO	1.17	2.10	3.27
MgO	....	0.09	0.09
H_2O, 110°	....	....	0.52
H_2O, ign.	....	....	1.56
			99.90

In the attempt to assign the results to various minerals an unexpected difficulty was encountered. Study of a thin section of this shale had shown the presence of a dull brownish mineral, agreeing with epidote in optical character, surrounding the quartz grains. Proceeding on the assumption that the calcium oxid was all present in this form, and calculating the corresponding amount of alumina, an excess of the latter, a considerable part of which is soluble in hydrochloric acid, was found to remain. While this may exist in part as unal-

tered kaolinite, it can not all be this mineral, for the water is too low by over one per cent. That some of the supposed magnetite might be an iron spinel (hercynite?) is not impossible, but in the absence of any means of ascertaining this, the calculation of the mineralogical composition has been made on a magnetite-kaolinite-epidote basis, the last being assumed to have Fe:Al = 1:2, for convenience, and gives:

Quartz, SiO_2	64.25
Epidote, $HCa_2Al_2FeSi_3O_{13}$	14.07
Kaolinite, (?) $H_4Al_2Si_2O_9$	17.00
Hematite, Fe_2O_3	2.47
Magnetite, Fe_3O_4	2.21
	100.00

The gray portion behaved in an entirely similar manner; its chemical composition was:

	Soluble in HCl.	Insoluble in HCl.	Totals.
SiO_2	0.20	77.14	77.34
Al_2O_3	2.57	7.28	9.85
Fe_2O_3	1.37	4.34	5.71
FeO	....	1.10	1.10
CaO	1.26	3.20	4.46
MgO	....	0.05	0.05
H_2O, 110°	....	....	0.44
H_2O	....	....	0.98
			99.93

And the minerals present may be calculated as:

Quartz, SiO_2	62.81
Epidote, $HCa_2Al_2FeSi_3O_{13}$	19.10
Kaolinite, (?) $H_4Al_2Si_2O_9$	14.50
Hematite, Fe_2O_3	0.07
Magnetite, Fe_3O_4	3.52
	100.00

Comparison of the mineralogical compositions of these different samples justifies the conclusions that the chief difference between the altered and unaltered shales consists in the state of combination of the iron and calcium; THE INDURATION PRODUCED BY THE IGNEOUS ACTION BEING PRINCIPALLY DUE TO THE CHANGE OF CALCITE INTO EPIDOTE, WHILE THE LOSS OF COLOR IS NOT DUE TO REMOVAL OF IRON, BUT IN PART TO THE ENTRANCE OF THAT ELEMENT INTO THE EPIDOTE MOLECULE, AND IN PART TO THE CHANGE OF HEMATITE INTO MAGNETITE.

ORIGIN OF DATOLITE AND THE ZEOLITES

THE origin of the zeolites and associated secondary minerals in igneous rocks has in the past been the subject of considerable discussion, and a wide difference of opinion appears still to prevail. Apart from the purely igneous mode of formation claimed by the earliest writers, and the contact-metamorphic origin advocated by Bunsen, the theories may all be grouped under two general classes,—first, attributing their formation to waters accompanying the eruption of the magma, and second, ascribing them to the subsequent action of circulating waters, of meteoric origin.

As principal exponents of the former view may be mentioned Beck,[8] Hawes,[9] Professor B. K. Emerson,[10] and Professor J. V. Lewis;[11] while the latter has been defended by J. D. Dana,[12] Fischer,[13] Professor R. Brauns,[14] and President C. R. Van Hise.[15]

The evidence favoring the former consists in—

(1) The fact that considerable water does accompany every eruption, and is given off as the magma solidifies.

(2) The fact that fluorine and boron are frequently present in the minerals in question, these elements being usually of magmatic origin. (Emerson.)

(3) The fact that the waters effecting the decomposition of the original rock and the development of the new minerals must have been free from oxygen, in that ferrous iron was not changed in the process. (Hawes.)

(4) The fact that the minerals first deposited are usually anhydrous, and the degree of hydration increases in the successive layers.

In opposition to these views it may be objected:—

(1) That zeolites are not known to form in modern lavas at the time of their extrusion, even though abundant water is present. (Dana.)

(2) That the fluorine and boron might be derived by the decomposition of primary minerals containing them, such as tourmaline or danburite. (Fischer.)

(3) That removal of oxygen dissolved in surface waters would be accomplished in the upper layers of the rock,—the belt of weathering. (Van Hise.)

(4) That the composition of the new minerals formed may well be determined by the chemical character of the solution rather than by the temperature. (Brauns.)

Careful consideration of these objections shows that they are not all of equal force. While it is no doubt true that zeolites do not form in modern sheets of lava a few feet thick, or near the upper surface of thicker sheets, neither have they been observed in corresponding positions in ancient lavas. The fine specimens from the Watchung Mountain of New Jersey are all found near the base of the flow, and in the small extrusive sheet here being studied, the datolite and zeolites first appear at a depth of 350 feet. And these minerals are actually found in the deeper portions of the Vesuvian lavas, as Dana himself admits. In fact, the limitation of the secondary minerals to the lower portions is a strong argument against the theory of their formation by circulating surface waters, for this process should develop them uniformly throughout a lava mass.

Fischer's suggestion, that the fluorine and boron of secondary minerals might have been derived from original tourmaline or danburite, while it may be valid in the case of the formation of the zeolites in granites and gneisses, which he was considering, is of no application here, for tourmaline and danburite are not known as constituents of lavas or similar igneous rocks. The appearance of these elements in the secondary minerals can further not be explained by any ordinary weathering process, unless they are present in the unaltered igneous rock as original constituents. No studies having ever been carried out with a view of testing this point, with the exception of those of Fischer, in which the methods employed were not sufficiently delicate to really settle the matter, a thorough investigation of it was here undertaken. This will be described after considering the two remaining arguments for the weathering theory.

The third objection raised is a perfectly sound one, but it merely shows that the presence or absence of oxygen during the formation of the secondary minerals is not adequate to determine the source of the waters effecting the change. The final argument that degree of hydration might depend on the chemical nature of the solution as well as on the temperature at which the minerals form is also by no means a conclusive one. Too little is known concerning the conditions necessary for the development of any of the secondary minerals for this to have much value in deciding such a question. So the only possibility of throwing any light upon the matter rests with the study of the distribution of boron and fluorine.

The elements boron and fluorine are among the most difficult to detect and determine known to the chemist. In fact, as far as fluorine is concerned, no absolutely certain method of detecting minute traces has as yet been devised.

With boron, however, there is a very delicate method of detection, the turmeric paper test, with which as little as 0.0001 milligram gives a distinct reaction. And for determination of small amounts in silicate rocks the writer has recently devised a method which is applicable, when carried out with special precautions, to quantities as small as .05 milligram, or, working on 1 gram of rock, to .005%.[16] For the present purpose it seemed unnecessary to attempt to obtain smaller quantities than this, for traces may be detected in practically every mineral substance, and could therefore have no significance here.

In the intrusive sheet at Jacksonwald no secondary minerals were observed. In the extrusive sheet, however, they are abundant, not in fine large specimens like those from the First Watchung Mountain in New Jersey, for instance, yet quite typical and definite. Considering the Antietam Creek section, already described in detail, at the very top of the mass the gas cavities are empty, or at best, filled with red mud, but ten feet down they are solidly filled with calcite, together with more or less chloritic material. About 100 feet below the top prehnite begins to appear, chiefly in seams solidly replacing the decomposed trap, but occasionally showing small globular clusters of crystals where a cavity has been occupied. This prehnite replacement is limited to a belt about 50 feet thick, although the same mineral occasionally accompanies the others in the cavities lower down. From 150 feet to 300 feet the calcite-chlorite filling is again the rule, and here the cavities are sometimes nearly an inch in diameter. Then datolite begins to appear, filling both bubble cavities and cracks, but never in large amount nor in distinct crystals, being instead coarsely granular and intimately mixed with calcite. The occurrence of this datolite is limited to perhaps fifty feet of thickness of the trap, and no trace of the mineral has been noted in any other part of the sheet, nor at any other exposure. Below the datolite zone, as it may be called, gas cavities are much less prominent, and here the zeolites make their appearance along the joint planes. These comprise stilbite, heulandite and chabazite, in small but typical crystals, the first usually alone, the last two usually associated; they are sparingly present through the remainder of the thickness of the sheet. At the very base there are a few elongated gas bubbles, mentioned above, and these are filled solidly or nearly so with white crystalline quartz.

Twenty specimens from all parts of this sheet were examined, and all but two of them, both from the datolite zone, proved to be free from boron. Of these exceptions, one was situated within an inch of a large cavity containing

datolite, and gave 0.165% B_2O_3, and the other showed a number of small bubbles filled with calcite and chlorite and gave 0.140%. In order to determine if possible the form in which the boron was present in these samples, they were treated with a heavy solution, acetylene tetrabromid, diluted with benzene. After several trials it was found that the boron mineral in both cases had a specific gravity of 2.8. As this mineral was further completely soluble in hydrochloric acid, there can be little doubt that it represents datolite, which in the first, has in part penetrated into the rock, as well as depositing in the cavity, and in the second, may well be present in some of the amygdules, but obscured by the more abundant calcite. The intrusive sheet proved entirely free from boron throughout its extent.

With a view to determining if similar relations existed elsewhere, attention was turned to the occurrence of boron minerals in other trap masses in Pennsylvania, and the sheet which crosses the Delaware River below New Hope, in eastern Bucks County, was studied in a similar manner. This sheet is of typical intrusive character, as is proved by the intense metamorphism of the sedimentary rocks overlying it, and by its coarse diabasic texture, without the slightest development of glass or of steam-bubble cavities, even at its uppermost surface.

The intensely altered shale immediately above the contact, as exposed along the river road, contains an abundance of minute crystals of black tourmaline, of peculiar lenticular shape, owing to the practical absence of faces in the prismatic zone; these become less frequent upwards, and at thirty feet above the trap disappear altogether, although alteration is evident through a thickness of over 1500 feet of shale. The amount of tourmaline present in a specimen obtained from as near the contact as possible was roughly estimated at one per cent, which would correspond to 0.1 per cent of B_2O_3, and analysis actually gave 0.105%. In a specimen from a distance of twenty-five feet above the contact 0.005% was found; while in the altered rocks from still higher horizons none could be detected. This tourmaline can certainly not have been produced by any weathering process, but must have been developed by the action of the intrusive trap, and its limitation to the lower 30 feet of altered shale indicates that the source from which the boron entering into its composition came could have been no other than the molten magma itself.

The trap at the contact was next investigated, and boron was found to be entirely absent from it, as from the traps at Jacksonwald, showing that this element must have been totally expelled during the crystallization of its constituent

minerals. In the "Goat Hill" quarry, some 800 feet below the top of the sheet, on the New Jersey side of the river, datolite had been discovered in fine crystals by Mr. Harry W. Subers and the writer about two years before, and one of the specimens then obtained was examined as had been done with the matrix of the Jacksonwald datolite. Here the trap was rather more compact, so that the datolite showed no sign of penetrating more than a few millimeters from the wall of the fissure in which it occurred. And the chemical examination failed to detect the slightest trace of boron in the samples of the rock used.

Since, then, boron is absent from the igneous rock as a whole at both localities, and must have been given off while the magma was in process of solidification, it follows that the datolite, and presumably the various associated secondary minerals as well, can not have been formed by a simple weathering process. It is not, however, necessary to assume that they developed immediately after the intrusion or extrusion of the magmas. For while the upper and lower surfaces of the sheets may have cooled rather suddenly, the interior portions no doubt required many years to attain the temperature of their surroundings, thus allowing time for the appearance of the joint planes in which many of the secondary minerals have deposited, and possibly even permitting the mingling of the magmatic with surface waters, so that the later minerals may have been formed by a combination of the two processes. The abundance of calcite as the last mineral to form throughout many trap masses certainly suggests the action of surface waters containing abundant carbon dioxid. All that can be concluded from the present study, however, is that THE DATOLITE AND ASSOCIATED MINERALS OBSERVED IN TRAP SHEETS HAVE PROBABLY BEEN FORMED DURING SOME STAGE OF THE COOLING, AND NOT BY SUBSEQUENT WEATHERING.

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